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MEASUREMENT AND INTERPRETATION OF CRUSTAL DEFORMATION RATES ASSOCIATED WITH POSTGLACIAL REBOUND

GRANT NAG5-1930

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I. Introduction

This project involves obtaining GPS measurements in Scandinavia, and using the measurements to estimate the viscosity profile of the Earth's mantle and to correct tide-gauge measurements for the rebound effect. Below, we report on several aspects of this project.

II. GPS Measurements

The permanent network set up by Onsala Space Observatory continues to operate, and the data are continuously being analyzed. The expanded DSGS was not occupied this year due to the unavailability of GPS receivers. We are currently planning the Summer Campaign, to take place in August, 1996. J.L. Davis, the P.I., will travel to Sweden early summer 1996 to plan these measurements and to prepare for publication several papers describing the GPS measurements from the last several years.

III. Summary of Fennoscandian Results to date

Appendix A contains a prepreint of a paper submitted to *Eos* and presented at the Fall 1995 DOSE investigators meeting in Pasadena. Appendix B comtains a paper appearing in *Nature* in January 1996.

IV. Relevant Publications

Davis, J. L., and J. X. Mitrovica, Sea level rise, mantle viscosity, and the anomalous tide gauge record of eastern North America, *Nature*, *379*, 331–333, 1996.

Davis, J. L., and J. X. Mitrovica, Sea level rise, mantle viscosity, and the anomalous tide gauge record of eastern North America (Erratum), *Nature*, *379*, 848, 1996.

Elósegui, P., Davis, J. L., J. M. Johansson, and I. I. Shapiro, Detection of transient motions with the Global Positioning System, in press, *J. Geophys. Res.*

BIFROST Project Members, First results from a continuously operating GPS network in Fennoscandia, submitted, *Eos*.

Davis, J. L., M L. Cosmo, and G. Elgered, Using the Global Positioning System to study the atmosphere of the Earth: Overview and prospects, submitted, *Proc IUGG General Assembly XXI*, 1995.

Appendix A. Paper submitted to *Eos* summarizing project results.

Submitted 1/10/96

First Results from a Continuously Operating GPS Network in Fennoscandia

BIFROST Project Members

Received ____________________; accepted ____________________

Short title:

Project BIFROST (Baseline Inferences for Fennoscandian Rebound Observations, Sea-level, and Tectonics) brings together investigators from five organizations in four nations (Table 1) for the purpose of acquiring and interpreting Global Positioning System (GPS) data in Sweden, Finland, and several other Baltic-area countries (Figure 1). The primary scientific goals of the project are to use the GPS determinations of three-dimensional crustal velocities associated with glacial isostatic adjustment [e.g. *James and Lambert*, 1993; *Mitrovica et. al*, 1993, 1994b] to estimate the viscosity of the Earth's mantle below Fennoscandia, to constrain the space-time history of the Late Pleistocene ice load in the region, and to correct the extensive Fennoscandian tide gauge record for the influence of vertical motions.

In spite of many years of active research, inferences of mantle viscosity based upon relative sea level (RSL) data continue to vary by an order of magnitude or more at all depths [e.g., *Nakada and Lambeck*, 1989; *Tushingham and Peltier*, 1992]. There are a number of possible causes for this disagreement. First, predictions of RSL variations are sensitive to not only the viscosity profile, but also the imprecisely known deglaciation history. Second, past analyses have been based mainly on forward solutions, and neither the resolving power nor the uncertainty associated with the inference have generally been assessed. The application of inverse methods to the data set [e.g., *Parsons*, 1972; *Mitrovica and Peltier*, 1993], though uncommon, has provided important insight in this respect, particularly in regard to the viscosity profile beneath Fennoscandia. A third cause for the discrepancy may be the influence of lateral heterogeneity in mantle strength. As an example, the inferences of *Nakada and Lambeck* [1989] are based upon RSL variations at Australian and Pacific island sites, and it is not clear that these inferences extend to the viscosity profile beneath Fennoscandia or Laurentia. Finally, the uncertainty associated with much of the global database of Late Holocene RSL curves is difficult to establish. Curves obtained from the same region are commonly significantly inconsistent, and in some cases uncertainties are so large that the data cannot be used to discern significant differences between Earth models. There is furthermore an inherent weakness associated with sea-level data sets: observations are only available along shorelines, which often provide sparse coverage.

The state of uncertainty in regard to mantle viscosity leaves recent determinations of sea-level change from modern tide-gauge data [e.g., *Peltier and Tushingham*, 1989; *Trupin and Wahr*, 1991; *Douglas*, 1991] also in doubt. The procedure for such determinations requires "correction" of the tide-gauge rates for the effect of glacial isostatic adjustment. These corrections are determined by performing calculations using specific profiles of viscosity. Reasonable variations in the viscosity used in the calculations, however, can lead to significant variations in the final estimated sea-level rise (compared to the stated standard deviation of that determination).

The BIFROST project was formed to address these fundamental issues. Being an international collaboration supported by a number of agencies, the BIFROST GPS network not surprisingly consists of several subnetworks. Thus far, the subnetwork which has produced the overwhelming majority of the data is SWEPOS, the 20-site Swedish permanent GPS network, which has been acquiring data continuously since August, 1993. In this article we will therefore concentrate on describing and presenting results from this network.

The standard SWEPOS site consists of a 3-m tall pillar, mounted on bedrock, on top of which is installed the GPS antenna with conical radome. (The site design for the sites of FinnNet, the Finnish permanent GPS array, is slightly different and will be described in a future paper.) The pillar is thermally insulated, and surrounded by heating coils. Removable scaffolds enable access to the tops of the pillars. Surrounding each pillar is a network of (typically) six pins covering an area typically of 15 m $\times$ 15 m. At intervals, once per year or more depending on the site, a theodolite is mounted on each pillar, targets are set up over the pins, and the local network is surveyed. Using these surveys, motions of the monuments relative to the local network of pins are monitored. No significant motion of the pillars has been detected in the 20 months of operation, with a limit of detection of ~0.5 mm or less.

At each site, a small (heated) house has been built to protect environmentally the GPS receivers, PCs, modems, and, if necessary, visiting operators. The houses, one of which is pictured in Figure 2, are provided with connections to power and telephone lines. (InterNet connections are envisioned for the future.) Each day, the data from all the GPS receivers are transferred via modem to an archival facility. The data are then transferred electronically (i.e., via the InterNet) for data analysis.

During the "pre-operational" period of SWEPOS (August 1993–December 1994), emphasis was of necessity placed on the assessment of equipment and the development of the data flow. During this testing phase, two related major error sources (several cm in the vertical, several mm horizontal) for continuous GPS networks were uncovered. We have determined that the incoming radiation scattered by the pillar on which the GPS antenna is mounted seriously distorts the received signals [*Elósegui et al.*, 1995]. This scattering produces an elevation-angle-dependent systematic error which can lead to large (cm or greater) errors in the estimated vertical coordinate of site position and which in principle affects all pillar-mounted GPS systems. The errors cancel to a high degree, however, for identical mounts with similar orientations (i.e., with parallel vertical directions), such as for the SWEPOS network. We are currently performing numerical simulations of the antenna-pillar system based on the method of moments [*Kishk and Shafai*, 1986], as well as tests with microwave absorbing materials, with the goal of developing an improved antenna-pillar system.

In addition to signal scattering caused by the pillars, snow which has accumulated on the radome appears to refract and delay significantly the incoming signal [*Jaldehag et al.*, 1995]. This phenomenon, observed also by *Webb et al.* [1995], produces an elevation-angle-dependent systematic error which causes cm-level or greater errors in the estimated vertical component of site position. A model for this effect [*Jaldehag et al.*, 1995] which includes refraction through a conical shell of wet snow of reasonable basal thickness provides an accurate quantitative description of the observed effect.

Although SWEPOS has been operational for only a few months (since December 1994), we have estimated baseline rates for those receivers which have been acquiring data during the pre-operational test phase, since August 1993. These data, as mentioned above, are problematic on account of signal scattering and snow propagation effects and also outages caused by power supplies inadequately shielded from electrical storm activity. To account for obvious snow effects we have removed any site position estimates with drastic "jumps" associated with precipitation. To account for the remaining, less obvious, snow effects, we have used a Kalman filter to estimate the rates. This Kalman filter models the vertical site position as the sum of a continuous vertical motion with constant rate plus a random walk.

The instrumental and environmental problems notwithstanding, the results thus far are extremely encouraging. Figure 3 shows estimates of vertical baseline rates from the SWEPOS GPS data plotted against rates predicted for two different Earth models. The predictions are based on the formalism of *Mitrovica et al* [1994a] and use Maxwell viscoelastic Earth models characterized by the PREM elastic structure [*Dziewonski and Anderson*, 1981], an inviscid core, an elastic lithosphere, and isoviscous upper and lower mantles, with the boundary between the two regions occurring at a depth of 670 km. The surface load history incorporates a gravitationally self-consistent ocean meltwater component and the ICE-3G model for the late Pleistocene deglaciation event [*Tushingham and Peltier*, 1991]. For both parts of Figure 3, the lithospheric thickness was taken to be 120 km and the lower mantle viscosity 2×10^{21} Pa s. For Figure 3a, an upper mantle viscosity of 10^{21} Pa s was used; for Figure 3b, a value of 0.5×10^{21} Pa s was used. The χ^2 (per degree of freedom) difference between the observed baseline vertical rates and the model rates is 3.1 for Figure 3a and 1.9 for Figure 3b. These measured rates are not yet sufficiently well determined to distinguish between the two viscosity models. Nevertheless, the "null model," which predicts no uplift, yields a χ^2 value of 6.9, which is significantly different than the χ^2 value for Figure 3b with a confidence of greater than 99%. Thus, we are able to report the first GPS detection of the broad-scale deformation associated with glacial isostatic adjustment.

Figure 4 shows a similar comparison between baseline vertical rates obtained from SWEPOS GPS data and those inferred from nearby tide-gauge data. (Only series of timespan > 70 years were used.) These vertical rates are based on the motion of one site with respect to that of another, and therefore the rates estimated from tide-gauge data are unaffected by any secular sea-level change common to all sites. The comparison is a good check on our results since it is independent of both the Earth model and the load history. (The only neglected effect is any secular tilt of the Baltic Sea due to adjustment of the geoid. However, this effect is most certainly less than 1 mm yr^{-1}, and probably smaller, and is thus negligible with respect to the current uncertainties. This effect will have to be accounted for as the accuracy of the rate estimates improve.)

The χ^2 difference between GPS and tide-gauge values in Figure 4 is 0.6 indicating an excellent fit relative to the uncertainties. This χ^2 difference is a factor of 3–5 smaller than the GPS-model χ^2 differences of Figure 3. There are two possible explanations for this large a factor. First, the GPS sites near to tide gauges, i.e., near coasts, might for some reason provide more accurate estimates of vertical uplift than inland sites. In the SWEPOS case, we expect such increased accuracy because these coastal sites generally experience less snowfall and therefore less snow accumulation and its concomitant effects (see above). The other possible explanation for the difference in χ^2 values is that there is a great deal of (artificial) "noise" in the predicted model rates. In this case we would not expect the accuracy of the predicted rates from coastal sites to be much different from that for inland sites. To test these possibilities, we have recalculated the χ^2 differences between the observed and model rates using only the subset of data used for the tide-gauge comparison. We find that the χ^2 differences for this subset are 0.8 for the model of Figure 3a and 0.9 for the model of Figure 3b. This result indicates that the observed rates from the inland sites are indeed less accurate, presumably due to the snow-propagation effect. (The χ^2 values for the inland sites are 4.7 and 2.6.)

Although the uncertainties associated with the GPS determinations of vertical rates are large with respect to those associated with the tide-gauge rates, they will decrease rapidly over the next few years. Nevertheless, even before the accuracy of the GPS rates equals that of the tide-gauge rates, the GPS rates will provide as much or more geophysical information than the tide-gauge rates because: (1) the greater geographic coverage of the GPS network (not being restricted to coastlines); and (2) the fact that the GPS provides "absolute" uplift, i.e., uplift relative to a satellite-based terrestrial reference frame rather than to the sea level. Further, we have yet to consider the horizontal motions, which are somewhat too small to be useful at present levels of uncertainty. To reach our observational goals, over the next few years we will continue our efforts to identify and eliminate, or at least quantify, effects associated with signal propagation and scattering, site instability, and orbit and reference frame errors.

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Table 1. BIFROST participants and applications.

Organization	Applications and Research Interests						
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Finnish Geodetic Institute	X	X		X		X	
National Land Survey (Sweden)	X	X		X		X	X
Onsala Space Observatory	X	X		X	X	X	X
Smithsonian Astrophysical Observatory	X	X	X		X		X
University of Toronto	X	X	X				

Key to applications: (a) Geodynamics/Mantle viscosity research
(b) Sea level/Global change research
(c) Ice history research
(d) Real-time positioning, navigation
(e) Atmosphere/Meteorology research
(f) Terrestrial reference systems determination
(g) Technique development/Accuracy improvement

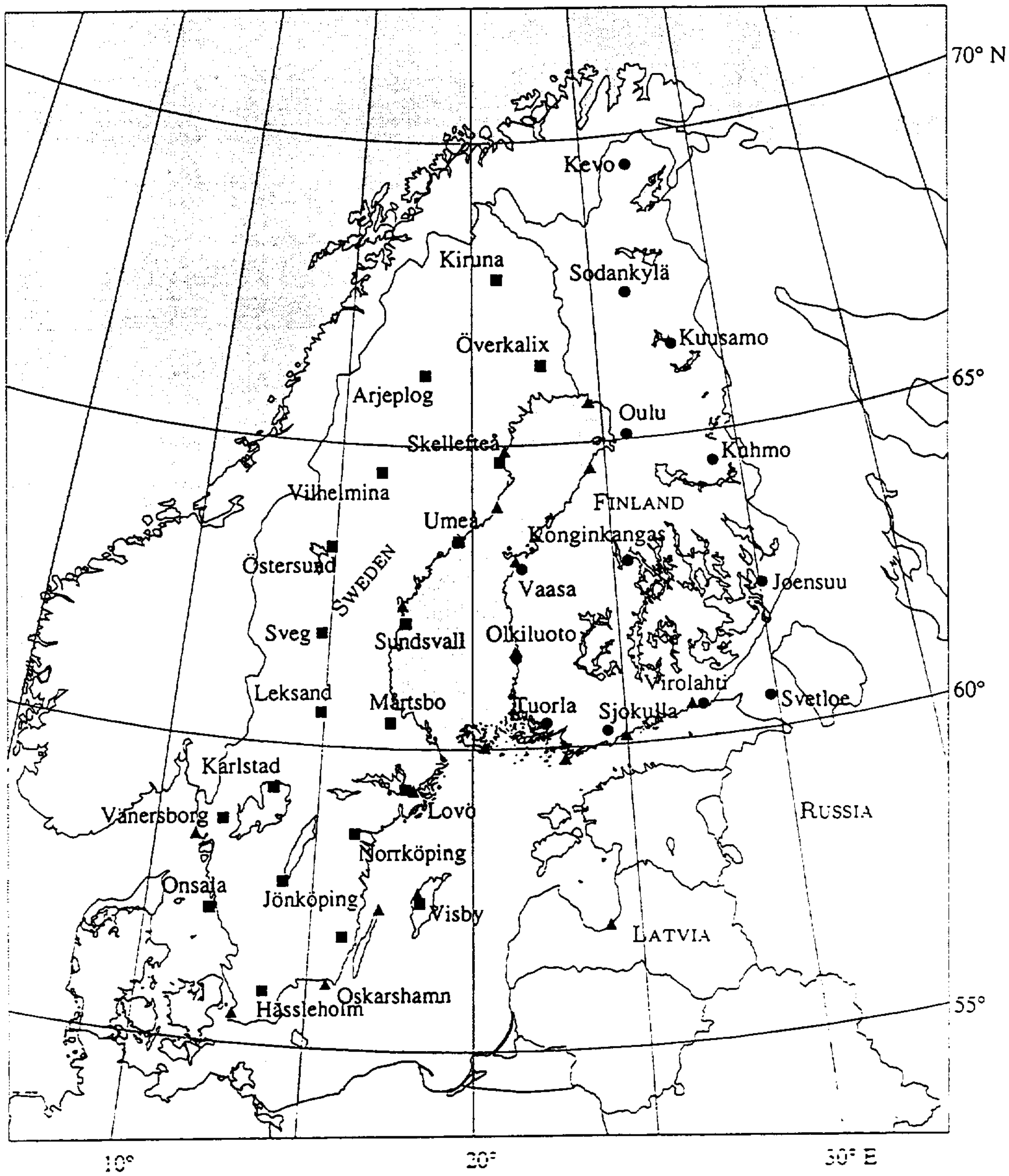
Figure Captions

Figure 1. Summary of the BIFROST GPS networks. GPS sites occupied are indicated by labeled squares (continuous and noncontinuous sites of the Swedish network), circles (present and future Finnish sites and Svetloe) and unlabeled triangles (tide-gauge sites occupied with GPS in August 1994). Sites of the EUREF campaign in September 1994 are not shown.

Figure 2. Photograph of the Sveg site of SWEPOS, showing the hut housing the GPS receiver and computer equipment, and the pillar and GPS antenna.

Figure 3. Comparison of observed and predicted model values for the vertical baseline rate. Baselines from Hässleholm to the other sites in SWEPOS are represented. A lithospheric thickness of 120 km and a lower mantle viscosity of 2×10^{21} Pa s are used for the calculations, along with an upper mantle viscosity of (a) 10^{21} Pa s and (b) 0.5×10^{21} Pa s.

Figure 4. Uplift rates, relative to that for the Hässleholm GPS site, obtained from the SWEPOS GPS data compared to relative uplift rates inferred from data from nearby (< 50 km distant) tide gauges.


70° N
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Kevo
Kiruna
Sodankylä
Kuusamo
Överkalix
Arjeplog
Oulu
Skellefteå
Kuhmo
Vilhelmina
FINLAND
Umeå
Konginkangas
Östersund
SWEDEN
Vaasa
Joensuu
Sveg
Sundsvall
Olkiluoto
Virolahti
Leksand
Mårtsbo
Tuorla
Sjökulla
Svetloe
Karlstad
Vänersborg
Lovö
RUSSIA
Norrköping
Onsala
Jönköping
Visby
LATVIA
Oskarshamn
Hässleholm

Fig 1

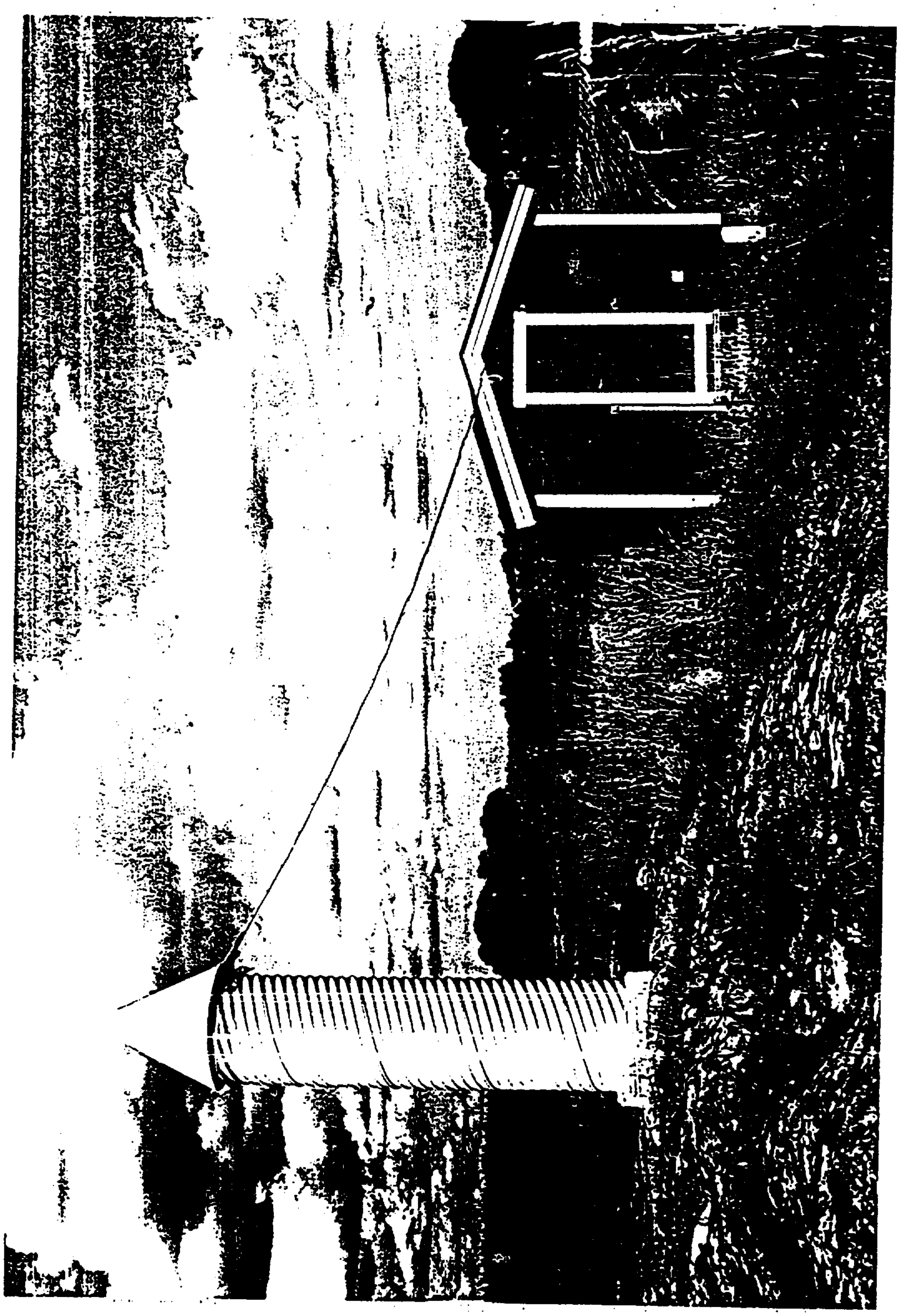


Fig 2

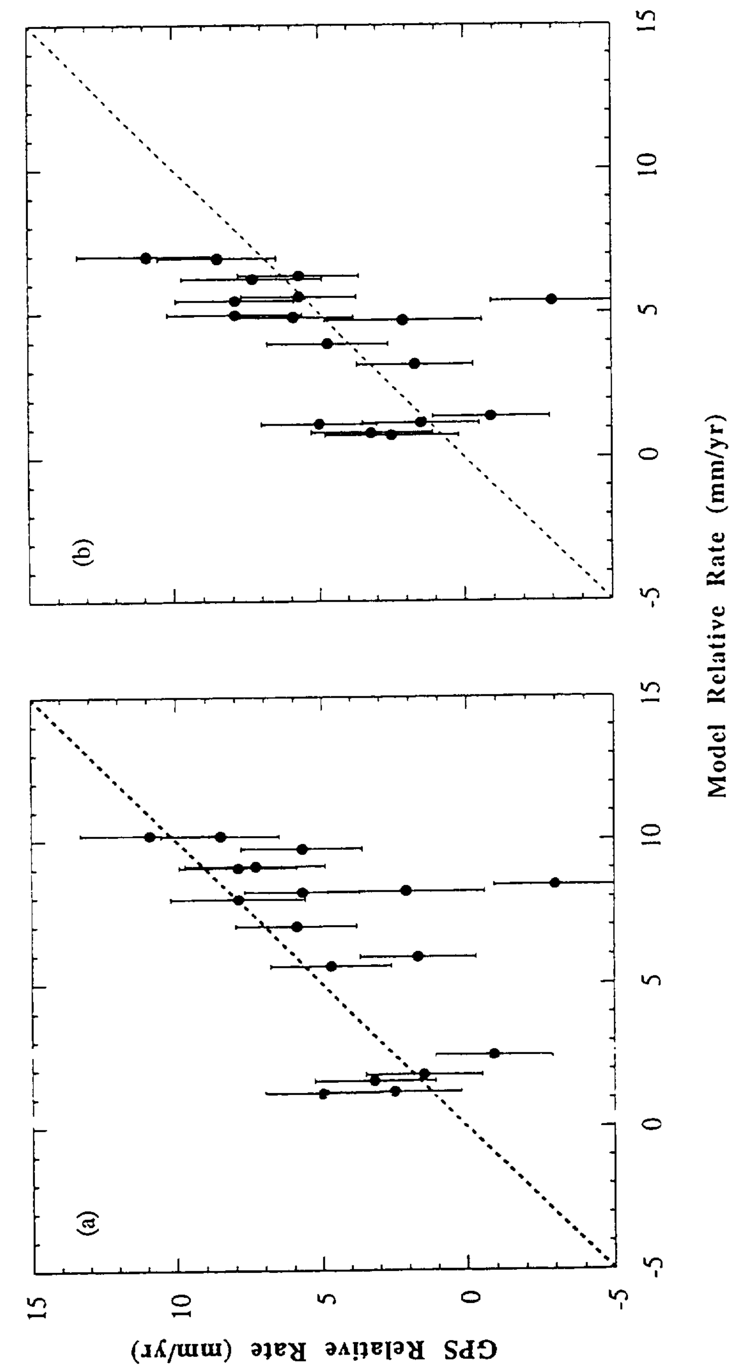
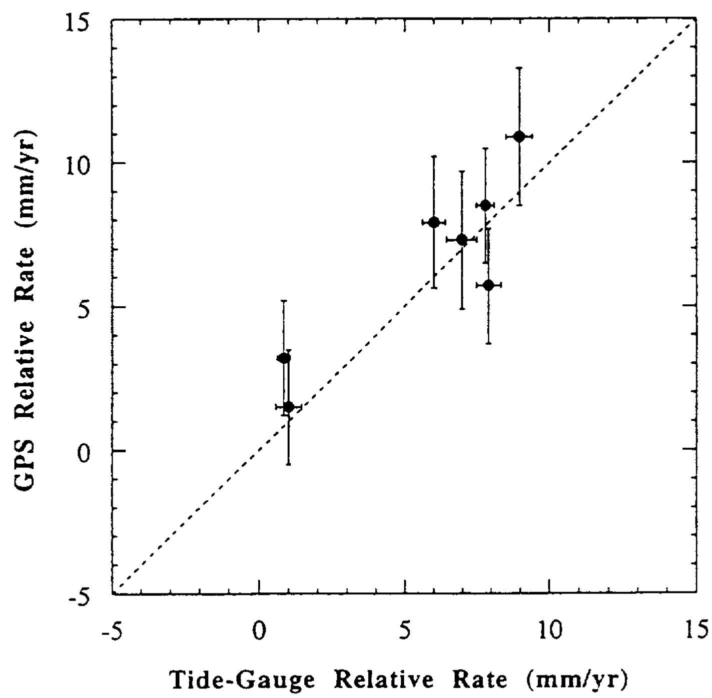


Figure 3



15
10
5
0
-5
-5
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15
GPS Relative Rate (mm/yr)
Tide-Gauge Relative Rate (mm/yr)

Figure 4

Appendix B

Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America

James L. Davis & Jerry X. Mitrovica

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Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America

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SEA-LEVEL variations, as recorded by the global network of tide gauges, represent a rich data set for studying a wide range of natural and anthropogenic phenomena, such as the sea-level rise induced by possible global warming. For this purpose, long-term sea-level trends must be corrected for the 'contaminating' effects of continuing glacial isostatic adjustment[1-5] (GIA). The numerical correction procedure has, for sites on the east coast of North America, yielded a set of highly anomalous sea-level rates characterized by systematic geographical trends[2,4,5]. We demonstrate that these trends are a consequence of inadequacies in the previous 'standard' numerical prediction for GIA. In particular, we find that the well-known trends in the GIA-corrected tide gauge rates are eliminated if the lower-mantle viscosity of the Earth model used in the GIA prediction is increased. This result obviates the need to explain the anomalous trend as a manifestation of Gulf Stream ocean circulation[4] or neotectonic processes[2].

We analyse the tide-gauge data from the east coast of North America using an iterative least-squares inversion in which the rates of sea-level change obtained from the raw data are taken as the observables, and parameters are estimated representing adjustments to the lithospheric thickness, the viscosity of the upper mantle, and the viscosity of the lower mantle. A common sea-level rate is also estimated. The *a priori* values for the Earth-model parameters were taken from the 'standard' model commonly used to generate GIA corrections[1,3-5]. This standard Earth model[6] is characterized by an elastic lithosphere of thickness 120 km, an upper-mantle viscosity of 10^{21} Pa s, and a lower-mantle viscosity of 2×10^{21} Pa s. The elastic structure of the Earth model was given by the seismically determined Preliminary Reference Earth Model[7]. As in previous analyses[1,3-5], we adopted the ICE-3G model[8] for the final Late Pleistocene deglaciation event. Partial derivatives with respect to the Earth-model parameters were determined numerically using sea-level rates calculated[9] for different parameter values. Our initial solutions clearly indicated that the sea-level rates favoured an increase of a factor of ~ 2.5 in the lower-mantle viscosity relative to the standard-model value. Furthermore, the formal uncertainty in this parameter was fairly small, indicating the high sensitivity of the fit to its value. Adjustments to the other two Earth-model parameters were small, and therefore had relatively little effect on the misfit. These parameters were therefore held fixed to the standard-model values for the inversions reported here. The 'raw' tide-gauge rates, together with the rates corrected using the standard and revised Earth models, are shown in Fig. 1. The scatter in the sea-level rates corrected using the revised model is a factor of ~ 3 smaller than that for the rates corrected using the standard model (Fig. 2).

The present-day rate of sea-level change due to GIA predicted by the standard model is characterized by a rapid sea-level fall to the northwest, associated roughly with the location of the ancient Laurentide ice sheet, and a moderate (0–3 mm yr^{-1}) sea-level rise in the 'peripheral bulge' area to the south and east (Fig. 3*a*). The sea-level fall in Canada is a manifestation of the uplift of the depressed solid surface in that region, whereas the sea-level rise is associated with the subsidence of the peripheral bulge that surrounds the central depression. The standard model predicts that the east coast of North America lies almost exclusively within the peripheral bulge region. Moving north from Florida along this coast the predicted sea-level rise increases monotonically up to a latitude of about 38° N. Between latitudes 38° and 43° N the variation in the predicted sea-level change is more gradual, as the 1.8 mm yr^{-1} contour roughly follows the coast. The curve representing the standard model (Fig. 1*a*) therefore has a nearly constant value between these latitudes.

We have found that the predicted location of the peripheral bulge is sensitive to changes in the lower-mantle viscosity, whereas variations of the upper-mantle viscosity and lithospheric thickness mainly affect the predicted amplitude of the peripheral bulge on a path traced along the North American east coast, at latitudes

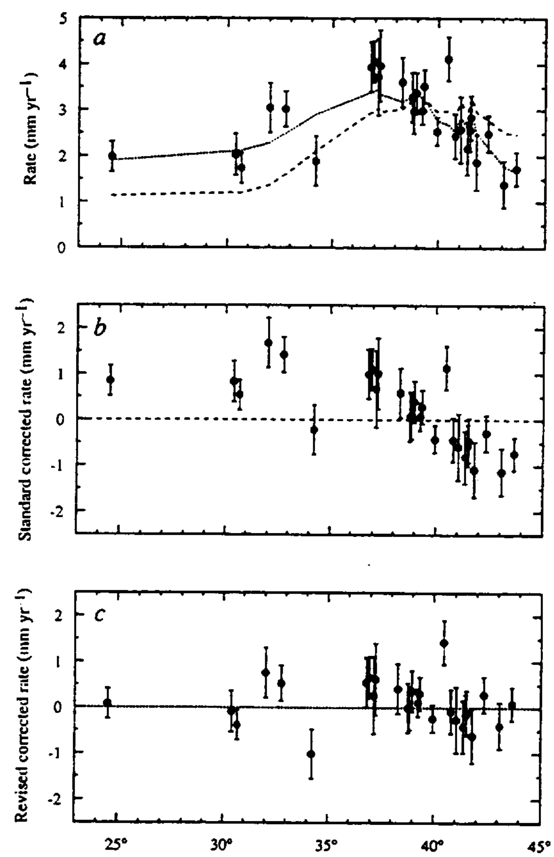

FIG. 1 Rates of sea-level change for the North American sites used in the analysis (error bars, 3σ). *a*, Raw tide-gauge rates (data points), and the GIA correction (dotted line) which has been shifted for the best-fitting coherent rate (1.5 ± 0.3 mm yr^{-1}) computed for the revised model. This model is characterized by a lower-mantle viscosity of 4.7×10^{21} Pa s. The analogous correction based on the standard model (defined in text) is shown by the dashed line. *b*, Residual tide-gauge rates corrected using the standard model, after fitting for a constant rate. *c*, Residual tide-gauge rates corrected using the revised model and the constant rate term. The residuals shown in parts *b* and *c* are related to the values in Table 1 by subtraction of the mean (common) sea-level rate of 1.5 mm yr^{-1}.

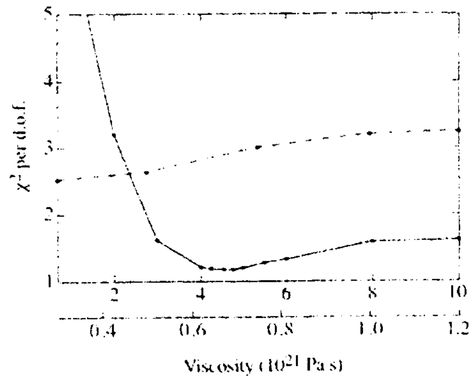

FIG. 2 χ^2 per degree of freedom (d.o.f.) as a function of lower-mantle viscosity (solid line, upper scale) and upper-mantle viscosity (dashed line, lower scale). The minimum χ^2 is achieved for a lower-mantle viscosity of 4.7×10^{21} Pa s. An *F*-test yields a level of significance of >99% for the decrease of the minimum χ^2 relative to that for the standard model. We also performed least-square solutions, with no further iterations after the initial adjustment, in which the lower-mantle viscosity and lithospheric thickness were estimated for a range of initial lithospheric thicknesses between 120 and 350 km. The estimated lower-mantle viscosity values were consistent (at the 1σ level) with 4.7×10^{21} Pa s, and the estimated lithospheric thickness values were consistent with, although slightly lower than, the standard value of 120 km.

below 45° N. The sensitivity of the peripheral-bulge dynamics to variations in mantle viscosity has previously been considered in some detail[10-13]. As the deep-mantle viscosity is increased, the boundary between the central uplift region and the bulge migrates away from the previously glaciated region (Fig. 3*a*,*b*), and the predicted sea-level rise due to GIA in the northeastern United States drops significantly. This sensitivity permits the revised Earth model to reconcile the trend evident in the sea-level rates determined from the raw tide gauge record (Fig. 1*a*,*c*); the revised model rates, as well as the observed rates, exhibit a decrease significantly sharper than that of the standard model north of 37 – 38°.

It has previously been noted[14] that the standard GIA correction does not reconcile the observed sea-level rate for the Key West site. In fact, the standard model (Fig. 1*b*) underestimates all except one of the sea-level rates south of 38°. The revised model fits the Key West rate and performs quite well for the southern sites generally (Fig. 1*c*).

Our simultaneous (revised) estimate of 1.5 ± 0.3 mm yr^{-1} for the common sea-level rise is significantly different from the

TABLE 1 Mean corrected sea-level rates

North Latitude	Standard corrected rate (mm yr^{-1})	Revised corrected rate (mm yr^{-1})	Rate uncertainty* (mm yr^{-1})
North American east-coast sites			
23 – 35	2.28	1.45	0.16
35 – 40	1.74	1.71	0.13
40 – 45	1.01	1.56	0.15
Far-field global sites			
8 – 58	1.6	1.4	0.4†

* Calculated using the 3σ errors of Fig. 1.
† Based on the weighted r.m.s. variation of the revised corrected rates about the weighted mean.

2.5 mm yr^{-1} cited by Douglas[4] for southern sites (south of New York) alone. In that analysis, the northern sites were found to yield a sea-level rise of 1.3 mm yr^{-1}, for a combined east-coast rate of 1.9 mm yr^{-1}. The separation of the data set into southern and northern parts was forced by the significant north–south geographical trend associated with sea-level rates corrected using the standard GIA model[4] (Fig. 1*b*). This separation is inconsistent with the notion that the residual rates reflect a globally coherent signal. In this regard, our revised model is consistent with both the southern and northern data (Table 1).

Douglas's global analysis[4] included 21 sites, 8 of which were located on the east coast of North America. We have found that the average sea-level rate determined by correcting the 'raw' rates at the remaining 13 sites is 1.4 mm yr^{-1} for a GIA correction based on our revised model, compared with 1.6 mm yr^{-1} for the standard model (Table 1). The revised model thus yields a highly coherent global (GIA-corrected) tide-gauge record.

Previous studies which have considered only the standard GIA correction have been compelled to invoke a variety of mechanisms to explain the anomalous geographical trend in Fig. 1*b*. Variations in ocean circulation can influence sea level[15], and it has been suggested that the anomalous trend may reflect the presence of the Gulf Stream[4]. However, the facts that the 'anomaly' is maintained for ~100 years and that the redirection of Gulf Stream flow occurs 3°–5° south of the dominant sea-level gradient in Fig. 1*b* militate against this explanation[4]. Following earlier suggestions that sea-level variations on the east coast may be influenced by neotectonic processes[16,17], the residual tide-gauge record derived using a GIA model based on a lower-mantle viscosity of 2×10^{21} Pa s has been used by others[2] to identify possible sites of such activity. Although seismicity along the Atlantic seaboard

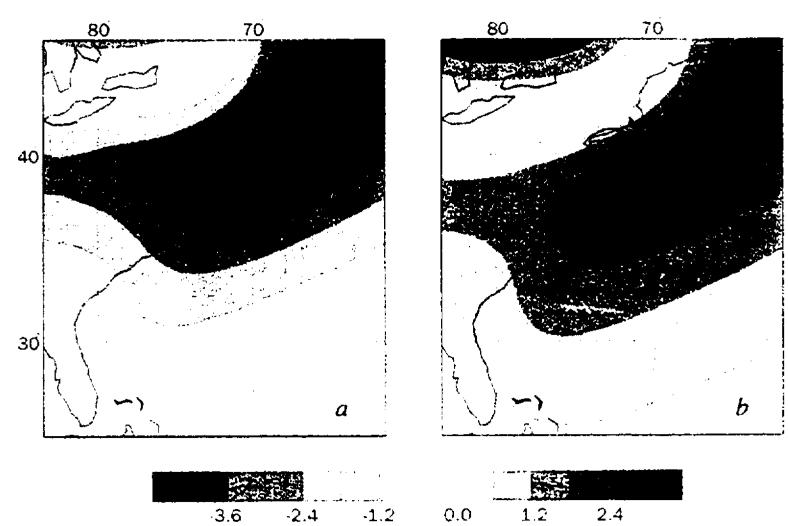

FIG. 3 Numerical predictions of the present-day rate of change of sea level (mm yr^{-1}; see colour scale) in the eastern United States due to GIA. The predictions were calculated using the ICE-3G deglaciation chronology[5] and: *a*, the standard Earth model; *b*, as *a*, except that the lower-mantle viscosity has been increased to 4.7×10^{21} Pa s. The tide-gauge sites used in the study are indicated by crosses.

suggests the possibility of neotectonic activity, appreciable crustal deformations are ruled out by geological evidence[18]. The influence of ocean circulation and neotectonism on long-term (secular) sea-level rates on the US east coast has not been directly quantified, and both would have to be characterized by a very specific geographical variation to reconcile the 'raw' sea-level trends shown in Fig. 1*a*. The required variation is, as we have demonstrated, accurately obtained using a GIA correction based on the revised model.

The lower-mantle viscosity of the revised model (4.7×10^{21} Pa s) is consistent with several other recent inferences based on postglacial ('historical') relative sea level variations in southern Hudson Bay and/or northern Europe[19,20]. Furthermore, models with a lower-mantle viscosity greater than the standard value, in combination with the ICE-3G deglaciation history[8], have been found to yield misfits insignificantly different from those obtained using the standard model when a global database of Late Pleistocene sea-level histories is considered[6]. When histories from the east coast of North America only are considered, a model similar to our revised model (lower-mantle viscosity 4×10^{21} Pa s) is in fact preferred[6]. The formal uncertainty in the revised lower-mantle viscosity ($\sim 0.2 \times 10^{21}$ Pa s when we propagate 3σ sea-level rate errors) is small, but may be somewhat misleading as it does not take into account deficiencies in the radial Earth model (for example, our simplistic description of the depth-dependence of viscosity) and ice-model errors[12,21]. Non-negligible secular trends in either oceanographic or neotectonic sea-level signals, if they exist at all, will only significantly affect the lower-mantle viscosity estimate insofar as they can mimic peripheral bulge migration. Lateral heterogeneities in lithospheric strength can influence GIA predictions[5], particularly at coastal margins[22-25], and may therefore alter our viscosity estimate. In this last case the main conclusion of this study would remain unaltered: the widely cited anomalous trend in GIA-corrected tide-gauge records from the North American east coast is entirely explicable in terms of inadequacies in the standard GIA model, and neither oceanographic nor neotectonic processes are required to explain the observations. □

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